VLBI observations of the 6.7 and 12.2 GHz methanol masers associated with NGC 6334F

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Introduction

The relatively recent discovery of methanol masers at 6.7 and 12.2 GHz (Batrla *et al.*, 1987; Menten, 1991) has doubled the number of strong maser transitions found in star formation regions. The complexity of maser pumping schemes has meant that the full potential of masers as probes of the physical conditions has yet to be realised. Despite this, interferometric observations of OH and H_2O masers have revealed much important information about the formation of massive stars (Genzel *et al.*, 1981; Bloemhof *et al.*, 1992). To date few similar observations of 6.7 and 12.2 GHz methanol masers have been published. However, those which have show that in many cases the 6.7 and 12.2 GHz methanol masers have a simple linear or curved spatial morphology (Norris *et al.*, 1988; Norris *et al.*, 1993).

Although the general distribution of maser spots can be determined by observations with connected element interferometers (e.g. ATCA or VLA), the smaller synthesised beam of VLBI observations means that the relative positions of maser spots can be measured with much greater accuracy. In addition, if there are two or more spots that have very similar velocities within the synthesised beam of a connected element interferometer then only one spot is observed, at a position which depends upon the relative flux density of the individual spots. However, for VLBI observations the size of the synthesised beam is much smaller than the typical separation of the maser spots, and so the position of each of the spots can be determined.

1

Observations and data processing

We have used VLBI observations involving five Australian antennas to image the 6.7 and 12.2 GHz methanol masers associated with NGC 6334F. The properties of each of the antennas is summarized in Table 1. The observations were made on 1992 May 29 and 31, between approximately 7 and 21 h UT on each day. The data were recorded using the MK II VLBI format, with 0.5-MHz bandwidth, and were correlated using the NRAO MK II correlator located in Soccoro, New Mexico. In spectral-line mode the NRAO MK II correlator processes one baseline at a time and produces a 96-channel autocorrelation spectrum for each antenna and a 192-channel complex cross-correlation spectrum for each baseline. The resulting velocity resolution (for uniform weighting) at 6.7 and 12.2 GHz is 0.28 and 0.15 km s^{-1}, respectively, and the velocity range 22.5 and 12.3 km s^{-1}, respectively.

After correlation, the data were calibrated and processed using the *AIPS* software package. The 12.2 GHz observations of NGC 6334F contained an unblended spectral feature which was strong enough to use for phase referencing. For the 6.7 GHz observation of NGC 6334F, neither phase referencing nor self calibration improved the signal-to-noise ratio of the images, presumably due to the complexity of the maser emission. Each of the spectral channels containing maser emission was imaged and CLEANed with "natural VLBI" weighting. This weighting scheme applies natural weighting to the fourth root of the original weights and was used to reduce the difference in weights between baselines.

The position and flux density of each maser spot was determined by fitting a two-dimensional Gaussian to the CLEANed image. The formal errors of the Gaussian fit for each of the imaging observations were 0.10–0.40 mas for the 6.7 GHz and 0.10–0.30 mas for the 12.2 GHz methanol maser images of NGC 6334F, but these values are probably underestimated. Fortunately, we have an independent method of estimating the accuracy to which the positions of the maser spots can be determined (see below), and we suggest that the accuracy to which the relative positions of the masers have been determined is better than 20% of the synthesised beam. For the 12.2 GHz observations where phase referencing was performed the accuracy is probably significantly better.

Results and Discussion

The compact H_{II} region NGC 6334F is one of the best studied sites of massive star formation at radio and far-infrared wavelengths (Ellingsen *et al.*, 1996; Gaume and Mutel, 1987; Loughgran *et al.*, 1986; McBreen *et al.*, 1979; Rodríguez *et al.*, 1982; Straw *et al.*, 1989). It is associated with some of the strongest known 6.7 and 12.2 GHz methanol maser emission. The 6.7 and 12.2 GHz VLBI images we obtained are shown on the same scale in Figs 1 and 2. The area of each circle representing a maser position is proportional to the flux density of that maser spot. There are three distinct clusters of 6.7 GHz methanol masers which we will refer to as NGC 6334F NW (north west), C (central) and S (south). At 12.2 GHz only the first two clusters are present and in each of these there are only approximately half the number of spots observed at 6.7 GHz.

The 12.2 GHz methanol masers have previously been imaged by Norris *et al.* (1988) using the Parkes-Tidbinbilla Interferometer (PTI). The 6.7 GHz methanol masers were also previously imaged by Norris *et al.* (1993) using the Australia Telescope Compact Array (ATCA). The maser distributions we observe agree well with those of Norris *et al.* (1988; 1993), with the exception of the two 6.7 GHz spots that they label C & E in the central cluster, which we did not detect. Either these features are variable and no longer detectable or, more likely, they result from a blending of several masers in the larger synthesised beam of the ATCA. For the less complicated 12.2 GHz observations the average difference between my VLBI positions and the PTI positions of Norris *et al.* is 3 mas, with the largest offset being only 5 mas. These two sets of observations are separated by four years and one month and this suggests that any proper motion is at a rate of $\lesssim 0.75$ mas yr^{-1}. Assuming that the distance to NGC 6334F is 1.7 kpc this corresponds to a velocity tangential to the line of sight of $\lesssim 60$ km s^{-1}. If the masers are seen edge on in circumstellar discs then the expected velocity tangential to the line of sight is less than 1 km s^{-1}, so that this observation does not provide a useful constraint on models of class II methanol masers. In total, Norris *et al.* detected twelve 6.7 GHz and five 12.2 GHz methanol maser spots, while our VLBI observations detected twenty 6.7 GHz and nine 12.2 GHz methanol maser spots.

The spectral morphology of 6.7- and 12.2 GHz methanol masers is often observed to be quite similar (Menten, 1991; Caswell *et al.*, 1995). If many of the individual maser spots at 6.7 and 12.2 GHz have the same line-of-sight velocities, then it seems logical to assume that they arise from the

same general area of the star formation region. Observations by Menten *et al.* (1992) and Norris *et al.* (1993) found the positions of some 6.7- and 12.2 GHz methanol masers to be coincident to within the positional errors of their observations. As has been noted by Menten *et al.*, this provides a stringent constraint on any pumping mechanism, as any scheme which produces 6.7 GHz methanol masers must also be able to produce 12.2 GHz methanol masers and *vice versa*.

Figs 1 and 2 show the 6.7 and 12.2 GHz methanol maser emission associated with the HII region NGC 6334F. A detailed examination shows that five of the nine 12.2 GHz methanol maser spots are coincident (to within ≈ 4 mas) with a 6.7 GHz methanol maser spot which has the same velocity (see Table). Figure 3 shows four of the five maser spots which are coincident for the two transitions. The rms difference between the positions of the five masers at 6.7 and 12.2 GHz is 3.7 mas, which is comparable to the relative positional accuracy. Thus it appears that the emission from the two transitions is truly coincident. This is supported by the observations of Menten *et al.* (1992) which had greater resolution and found positional coincidence to within 1–2 mas. Further supporting evidence is that the rms difference between the 6.7 and 12.2 GHz positions we observed is dominated by the R.A. offset (3.6 mas as opposed to 0.7 mas for the Decl. offset) and the beam shape of these observations was significantly elongated in R.A.

If we assume that the five maser spots are coincident, then the observed difference in the positions at the two frequencies will depend upon the accuracy to which the relative positions of the maser spots have been estimated by the processing technique outlined above. As the 6.7 GHz observation did not use phase referencing and had a larger synthesised beam, it would be expected to have greater errors in the relative positions of the masers than the 12.2 GHz observation. If it is assumed that the difference in the positions of the coincident spots results purely from the errors in relative positions of the masers at 6.7 GHz then observed rms difference between the 6.7 and 12.2 GHz spots implies errors of 17% and 5% of the synthesised beam for the R.A. and Decl. components respectively.

Conclusions

We have made milliarcsecond resolution images of the 6.7- and 12.2 GHz methanol maser emission associated with the well-known star formation region NGC 6334F. The images agree well with previous lower resolution ob-

4

servations, but detect approximately double the number of spots seen in the earlier work. Comparison of the relative positions of the 6.7 and 12.2 GHz maser spots shows that five of them are coincident to within the positional accuracy of these observations ($\approx$ 4 mas). Menten *et al.* (1992) observed similar positional coincidence for W3(OH) and in each case the flux density of the 6.7 GHz maser spot was greater than that of the 12.2 GHz methanol maser spot. However, for NGC 6334F several of the coincident maser spots have a larger flux density at 12.2 GHz than at 6.7 GHz. We also detected several 12.2 GHz methanol maser spots with no coincident 6.7 GHz emission. This implies that, although the 6.7 GHz methanol masers usually have a greater flux density than their 12.2 GHz counterparts, regions within the gas cloud exist where the conditions are more favourable for 12.2 than for 6.7 GHz methanol maser emission. Further milliarcsecond resolution observations of both 6.7 and 12.2 GHz methanol masers are required to determine the distribution of 6.7:12.2 GHz methanol flux density ratios. If the conditions which give rise to the various observed ratios can be determined, then VLBI images of class II methanol masers will allow the physical conditions of the star formation region to be probed with unprecedented resolution.

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Table 1: The diameter, polarization and system equivalent flux density characteristics at 6.7 and 12.2 GHz for the 6 antennas which participated in the VLBI observations. RCP = Right circular polarization; SEFD = System equivalent flux density

Antenna	Diameter	6.7 GHz		12.2 GHz	
		Polarization	SEFD	Polarization	SEFD
	(m)		(Jy)		(Jy)
Culgoora	22	RCP	1550		
DSS 43	70			Linear	400
Hartebesthoek	26	RCP	1400	RCP	1400
Hobart	26	RCP	1800	RCP	4000
Mopra	22	RCP	1100	Linear	2200
Parkes	64	RCP	100	RCP	140

Table 2: Table of coincident 6.7 and 12.2 GHz methanol masers for NGC 6334F.

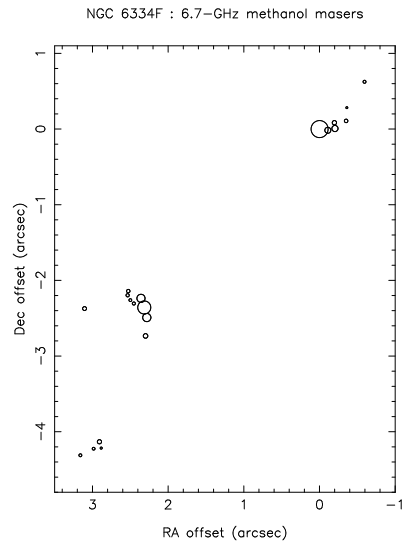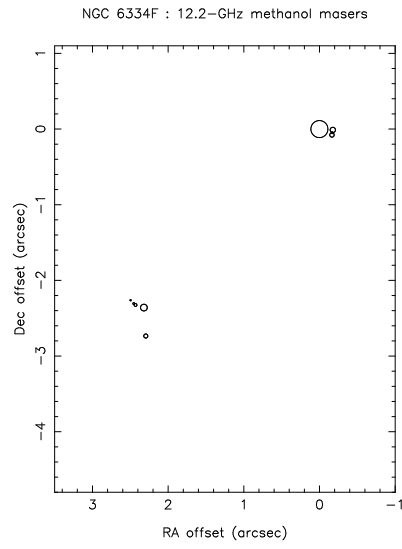| 6.7 GHz methanol masers				12.2 GHz methanol masers				Difference	
Velocity LSR (km s^{-1})	RA offset (arcsec)	Dec offset (arcsec)	Flux Density (Jy)	Velocity LSR (km s^{-1})	RA offset (arcsec)	Dec offset (arcsec)	Flux Density (Jy)	RA offset (arcsec)	Dec offset (arcsec)
-11.1	0.0000	0.0000	129	-11.3	0.0000	0.0000	246	0.0000	0.0000
-10.6	2.2999	-2.7332	9	-10.8	2.2943	-2.7346	14	0.0056	0.0014
-10.4	2.3168	-2.3573	76	-10.5	2.3192	-2.3588	38	-0.0024	0.0015
-9.9	2.4548	-2.3049	4	-9.8	2.4536	-2.3055	3	0.0012	0.0006
-9.0	2.5009	-2.2602	4	-8.9	2.4951	-2.2620	1	0.0058	0.0018

Figure 1: The relative positions of the 6.7 GHz methanol masers associated with NGC 6334F. The area of the circle marking the position of each maser spot is proportional to its flux density. The images were made using a 21.4 x 15.5 mas synthesised beam.

NGC 6334F : 12.2−GHz methanol masers

Figure 2: The relative positions of the 12.2 GHz methanol masers associated with NGC 6334F. The area of the circle marking the position of each maser spot is proportional to its flux density. The images were made using a 12.3 x 2.5 mas synthesised beam.
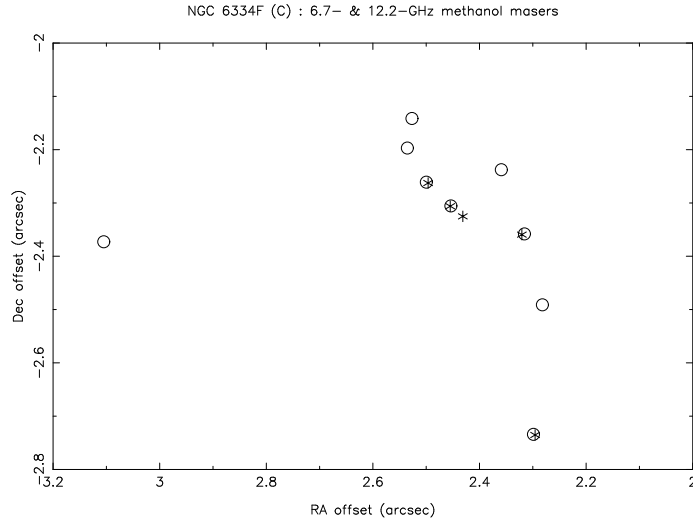
Figure 3: The relative positions of the 6.7 GHz methanol masers associated with NGC 6334F (C) are marked by open circles and the 12.2 GHz methanol masers are marked by stars.